WADC TECHNICAL REPORT 52-14

AD 52-77

THE EFFECT OF DIFFERENT PREADAPTING LUMINANCES ON THE RESOLUTION OF VISUAL DETAIL DURING DARK ADAPTATION

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JULY 1952

WRIGHT AIR DEVELOPMENT CENTER

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July 1952

Wright Air Development Center
Air Research and Development Command
United States Air Force
Wright-Patterson Air Force Base, Ohio

FOREWORD

This report was prepared by Columbia University under USAF
Contract No. AF 33(038)-22616 covering work on Visual Factors
in Cathode Ray Tube Data Presentation. The contract was
initiated under a project identified by Research and Development
Order No. 694-45, "Presentation of Data on Radar Scopes," and was
administered by the Psychology Branch of the Aero Medical Labor-
atory, Directorate of Research, Wright Air Development Center,
with J. M. Christensen acting as Project Engineer.

ABSTRACT

Luminance thresholds for the resolution of various widths of grating line were determined during dark adaptation following light adaptation to luminances of 11,200, 1290, 100, and 0.98 millilamberts. Dark adaptation curves for the finest gratings, representing high visual acuity, start at a high initial luminance and drop to a final steady level after 5 to 12 minutes in the dark, as is characteristic of cone function. Curves for coarser gratings may display both cone and rod portions, or after light adaptation to low luminances may represent rod function only. The higher the degree of resolution required the higher the position of the dark adaptation curve with respect to the log threshold luminance axis. Increasing the level of light adaptation results in higher initial threshold luminances and a more gradual decline to a final steady value. The final steady value of threshold luminance for a given value of acuity is little influenced by the level of light adaptation.

These results are of practical importance in many Air Force situations. Consider, for example, the radar bombardier who may have to shift his attention from levels of high illumination (sunlit clouds) to levels of low illumination (radar scopes). Complete recovery of cone acuity may require as much as five minutes, although fairly adequate acuity returns within one minute. As long as the brightness differential is limited to a ratio of 500 to one or less, acceptable visual acuity is recovered within one second. As the brightness ratio increases above 500 to one, the immediate loss in acuity in shifting to the lower brightness levels increases rapidly. From these data it is possible to specify the brightness differentials that can be tolerated in the performance of many common Air Force tasks.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDING GENERAL:

ROBERT H. BLOUNT
Colonel, USAF (MC)
Chief, Aero Medical Laboratory
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INTRODUCTION

Variation in threshold luminance for the detection of light during
the course of dark adaptation has been extensively investigated. Log
threshold luminance values plotted against time in the dark decline with
a decrease in slope, until after about thirty minutes there is very little
further decline in the threshold value. The actual form of the curves
depends on the condition of light adaptation prior to dark adaptation and
the portion of the retina tested. When areas which include both rods and
cones are tested, the resulting curves may be of duplex character, with an
initial portion falling off with decreasing slope until a plateau is reached
which represents minimum cone threshold, and then a subsequent further
decline in threshold representative of rod function. This description
of the break in terms of the duplicity theory is now widely accepted (8).

The character of dark adaptation curves is markedly affected by both
the luminance and duration of preadaptation. When preadaptation is at a
high luminance or of long duration, the decline in threshold with time is
gradual and manifests a marked cone portion. Preadaptation at low lumin-
ances or for short durations results in more rapid dark adaptation with
relatively less well marked cone portions. The effects of luminance level
and duration of preadaptation and the implications of these effects in
terms of the photochemical theory of retinal sensitivity have been dis-
cussed by Winsor and Clark (19), Wald and Clark (16), Johannson (11),
Haig (7), and Hecht, Haig, and Chase (9).

Threshold values obtained are also influenced by the color, area,
and duration of the test flash. The difference between minimum thesholds
for rods and cones has been shown to depend on the photochromatic interval
at the wavelength used in measuring threshold (9). An increase in area
(4), or an increase in the duration of the test flash (6, 12) up to
critical duration result in a lowering of absolute threshold.

Several investigations have studied other thresholds than those for
simple light detection during dark adaptation. Miles (14) reports an
experiment in which the course of threshold changes during dark adapta-
tion was determined for a test pattern representing an airplane silhouette,
presentable in any one of four orientations. Luminance thresholds were
determined for identification of the orientation of the silhouette, for
the recognition of form, for light detection with the silhouette test pat-
tern, and for light detection with an open circular test pattern of the
same overall size as the silhouette test pattern. Threshold curves were
found to be successively lower for each of the criteria in the order listed.

Craik and Vernon (3) determined threshold luminances for identi-
fication of the orientation of a pointer after 12, 20 and 40 minutes of
dark adaptation, and compared these values with light detection thresholds
for a number of subjects. The level of theshold for identification ap-
peared to be closely related to level of threshold for light detection.

In the experiment cited above by Hecht, Haig and Chase, the criterion used was recognition of a cross rather than simple light detection. The authors state that the only effect of this criterion was to raise threshold values approximately 0.3 log unit.

In a recent experiment, Wolf and Zigler (20) investigated the threshold luminance for the resolution of parallel lines subtending a visual angle of 0.26 degree during dark adaptation. Light adaptation was at a level of 2193 millilamberts and of ten minutes duration. Square test patches of four different areas were used, and determinations made in the fovea and parafovea. Thresholds were determined for light detection without the lines in the test field, for light detection with the lines in the test field, and for resolution of the lines. In all cases the dark adaptation curves for resolution threshold were roughly parallel to the curves for light detection threshold.

Visual resolution, or acuity, which is defined as the reciprocal of the just resolvable visual angle in minutes of arc between adjacent contours subtended at the eye, has been studied extensively by Shlaer (15) who used both a broken ring, and gratings of parallel lines and spaces of equal width. Visual acuity was found to increase with increased illumination of the test object up to an absolute maximum which depended on the type of test object used. Graham and Cook (5) also found an increase in acuity with an increase in the illumination of grating test objects. In addition, they found intensity and duration of test flash to be related according to the Bunsen-Roscoe law for short durations.

On the other hand, Martin and Kaniowski (13) found that for certain visual angles the frequency of correct identifications of the orientation of a double star test object increased to a maximum with increased intensity of the test flash and then subsequently decreased when intensity was further increased. Adaptation was apparently maintained constant for all determinations. Craik (2) reports that acuity increases with illumination as long as the level of adaptation of the eye is the same as the illumination, but that acuity decreases when the level of illumination of the test object is much higher than the level of adaptation of the eye. Wilcox (18) found that visual acuity continued to increase with increase in background luminance when dark parallel bars were used. With increase in luminance of light bars on a dark background, however, acuity increased to a maximum and subsequently decreased.

Brown, Graham, Leibowitz and Ranken (1)[a]/ determined threshold luminance during dark adaptation for five grating test objects representing visual acuities of 1.04, 0.62, 0.25, 0.083, and 0.042 as well as threshold luminance for light detection with no grating in the test field. Preadaptation was at a level of 1500 millilamberts and of five minutes duration. The cone portions of the resulting curves were all approximately parallel to the cone portion of the light detection curve. Rod portions were obtained only with the two gratings representing visual acuities of 0.042 and 0.083 since the rods were apparently not functional

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a/As a result of a discrepancy in the calibration, all tabular values in this earlier report require a correction of -0.65 log unit.

in the resolution of the finer gratings. The rod portions for these two gratings appeared to deviate slightly from parallel with the rod portion of the curve for light detection, but the variability of the points determining these curves make such deviation uncertain. In general, the implications of these results are to the effect that the course of dark adaptation curves is unaltered by the visual resolution criterion.

The purpose of the present experiment is to determine the course of luminance threshold curves for acuity objects during dark adaptation following different preadaptation luminances.

The results will provide an additional basis for evaluating effects of preadapting luminances by a criterion test measure other than the light detection threshold. Specifically, the experiment asks: Is the course of dark adaptation independent of the level of test flash luminance?

Preadapting luminances of 0.98, 100, 1290 and 11,200 millilamberts were used. The duration of pre-exposure was five minutes in every case. Threshold curves were obtained for each of these preadaptation conditions using test objects which represented acuities of 0.62, 0.25, and 0.042, as well as for light detection with no grating in the test field.

APPARATUS AND PROCEDURE

The apparatus was a Hecht-Shlaer adaptometer (10) modified so that gratings could be inserted in an area centering about a red fixation cross (1).

Threshold determinations were made with the optical system which is represented diagrammatically in Figure 1A. The light source G is a circular ground glass window 20 mm in diameter placed in a lamp housing M containing a seasoned (24 hour) 100-watt tungsten filament frosted bulb. The lens L_1 is located at its focal distance of 12 cm from the source. Parallel light emerging from L_1 passes through a field stop B 4.45 cm in diameter which limits the size of the test field to 7.3 degrees. The parallel light next enters the lens L_2 which has a focal length of 36 cm. The light is thus converged forming a Maxwellian view at the exit pupil EP which is located at the principal focus of L_2. The exit pupil is 3 mm in diameter. The lens system is such that an image of the grating test object T is seen at a distance of 57.2 cm from the exit pupil EP.

The wedge and balancer W directly in front of the source cover a density range of 2.4 log units. By placing Wratten neutral tint filters NN in a filter rack and adjusting the wedge, test field luminance is varied over any desired amount. The duration of the test flash is controlled by a photographic shutter S located between the wedge and the filter rack. The fixation cross F is reflected into the optical axis by a thin piece of cover glass R, 0.007 inch thick, at 45 degrees to the axis and located between the grating and L_1.

The cross was set at approximately the same optical distance from the eye as that of the gratings and then more carefully positioned by setting it so that monocular movement parallax was eliminated. The cross served as a cue for accommodation. The length of its arms subtend a
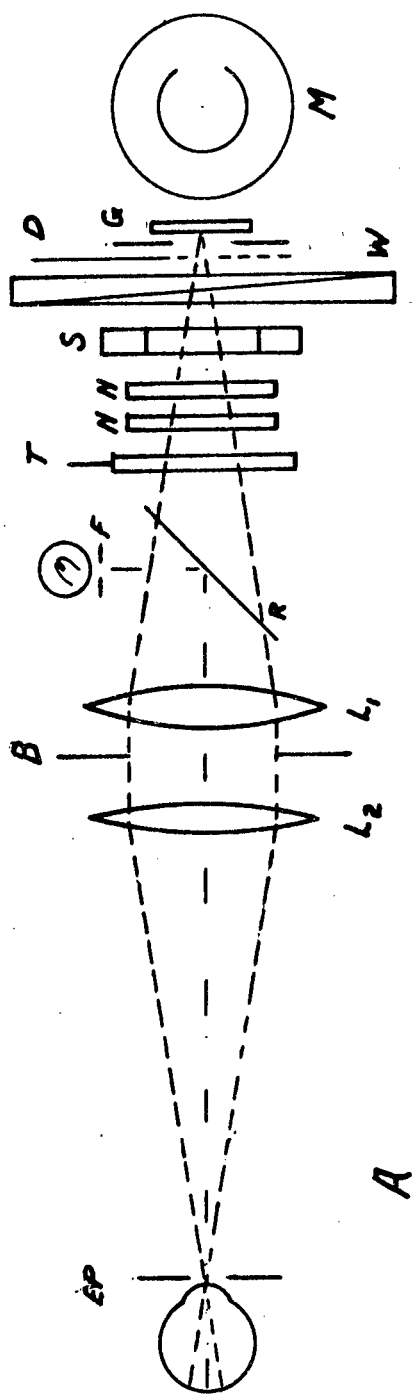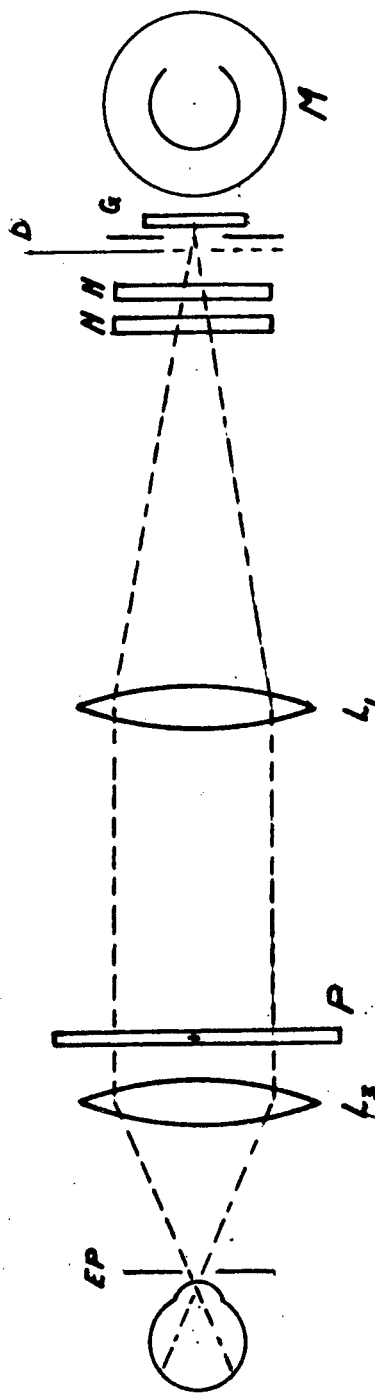
FIGURE 1: SCHEMATIC DIAGRAM OF THE OPTICAL SYSTEMS OF THE APPARATUS. (MODIFIED FROM HECHT AND SHLAER, 1938.) THE UPPER DIAGRAM, A, IS THE SYSTEM USED FOR THRESHOLD MEASUREMENTS. THE LIGHT ADAPTATION SYSTEM IS REPRESENTED BY THE LOWER DIAGRAM, B. SEE TEXT FOR AN EXPLANATION OF SYMBOLS.

visual angle of 22 minutes and the width of the arms subtend approximately three minutes. The observer was instructed to keep the brightness of the cross just above threshold by means of a rheostat located inside the dark room as the eye became dark adapted.

The optical system used for light adaptation is represented diagramatically in Figure 1B. It employs the same light source as that used for threshold determinations. Light from the source is collimated by lens L_1 and the parallel rays emerging from this lens next enter a converging lens L_3 having a focal distance of six cm. The exit pupil EP is six cm in front of L_3 at its principal focus. This lens system forms an image of the source G at the exit pupil EP. To the eye of the observer placed at the exit pupil, L_3 appears filled with light, and provides an adapting field of approximately 35 degrees in diameter.

Fixation during light adaptation is provided by a small cross scratched on a piece of plain glass P between the two lenses and 5 cm from L_3. The image of the cross is at a distance of 36.3 cm from the eye of the observer. Level of light adaptation can be varied with Wratten neutral tint filters NN located between the ground glass window and the first lens.

The two optical systems for light adaptation and threshold determination are readily interchangeable by shifting a lever on the side of the apparatus. This enables the determination of threshold to be made early in dark adaptation since it is unnecessary for the observer to reposition his head between light adaptation and the first test flash. Accurate timing of the interval between the end of light adaptation and the presentation of the first test flash is afforded by means of the shutter D and an electric timer. Closing a switch simultaneously causes shutter D to close and the timer to start. At the end of the interval for which the timer is set, a circuit closes which automatically trips shutter S. It is necessary for the experimenter to shift the lever on the side of the apparatus during the brief interval between the time shutter D closes and shutter S is tripped. Movement of the lever causes shutter D to reopen preparatory to the presentation of the first test flash.

The luminance of the light adaptation field was determined by means of a binocular match. The luminance of the uniform circular field of the matching device when its lamp was operated at a specified current was first measured carefully with a Macbeth Illuminometer. It was then viewed with one eye through a three mm artificial pupil while the light adapting field was viewed through the three mm pupil of the apparatus with the other eye. The visual angles of the two fields were equated by means of a variable iris diaphragm which was placed next to the six cm lens in the apparatus while making the determination. The luminances of the two fields were equated by placing appropriate filters in the light adaptation filter holder. All filters had been accurately calibrated previously using a Martens photometer. Two different individuals served as observers, and observations were made using first the right and then the left eye to view the matching standard. The maximum luminance of the light adaptation field was thus determined to be 14,800 millilamberts with the 100-watt bulb operated at 120 volts dc.

The test field luminance was measured using the monocular matching device especially designed for the purpose. The device was suspended directly in front of the 35 cm lens, and the observer viewed a split circular field, half of which was illuminated by the test light and the other half of which was illuminated by a previously measured source in the matching device. The two halves of this field were carefully matched by the observer who adjusted the position of the neutral density wedge by means of a cable control. Ten settings of the wedge were made by each of two observers and the resulting values averaged. The maximum luminance of the test field thus determined was 15,140 millilamberts when the 100-watt bulb was run at 120 volts dc.

Calibration of the neutral density wedge and balancer was checked by placing different filters of known density in the filter holder, obtaining a match with the monocular matching field by adjusting the wedge, and checking the difference in density indicated by the difference in setting of the wedge against the difference in density of the filters used.

The gratings used in the experiment were three of those described by Shlaer (1915). They had 10, 60, and 150 opaque lines per inch respectively, and the lines were separated by transparent spaces equal in width to the lines. The visual angles subtended by the distance between contours on these gratings were calculated in the following manner. A scale was placed up against the 35 cm lens on the observer's side with the ten lines per inch grating in position in the grating holder. The number of lines in the grating image along one inch of the scale was counted, and from this value and the distance of the scale from the eye, the visual angle subtended by the width of one line or space was calculated. The visual angles for the other two gratings were 1/6 and 1/15 of this value respectively. The visual angles were also calculated from the known width of the lines, the magnification of the optical system, and the optical distance of the grating image from the eye. There was good agreement between the results of the two methods of measuring line thickness.

Data were obtained for two observers, one male and one female, both of whom were emmetropic, of better than average visual acuity on the basis of clinical standards, and unastigmatic. The head of the observer was positioned by a chin rest during light adaptation and for all test flashes during dark adaptation. All determinations were made using the right eye.

Light adaptation luminances of 0.98, 100, 1290, and 11,200 millilamberts were used. With the lowest of these, the observer was dark adapted for ten minutes before the beginning of light adaptation. About 30 seconds before the end of this period he was given a ready signal, at which time he positioned his chin in the chin rest and fixated the red fixation cross. One second before the beginning of light adaptation the experimenter said "ready," and then shifted the lever on the side of the apparatus changing to the light adaptation system. This resulted in the red fixation cross being replaced by the 35 degree circular field in the center of which was a small dark fixation cross at approximately the same position in which the red cross had been. This field was viewed for five minutes, the observer maintaining central fixation with the aid of the cross. Fifteen seconds before the end of the five minute period the observer was given a ready signal, followed by another at one second before the end of the

period. Precisely at the end of the five minute period the lever was
again shifted, changing back to the optical system used for test flashes
during dark adpation. Four seconds after the beginning of dark adapt-
ation the experimenter said "ready", and the first test flash was presented
at five seconds after the beginning of dark adaptation. The mechanism for
automatically timing the interval after light adaptation was not used in
determining the five second points. All test flashes were of 0.016 second
duration. After the first flash, flashes were presented regularly on the
odd minutes after the beginning of dark adaptation starting at one minute
and continuing to 29 or 31 minutes. In each case the experimenter would
warn the observer 15 and again at five seconds before the test flash, as well
as saying "ready" one second before the flash was presented. This enabled the
observer to become accommodated for the cross before the flash was given.
The procedure was exactly the same with the other three levels of preadaptation
except that only five minutes of dark adaptation preceded light adaptation
to 100 and 1290 millilamberts, and there was no dark adaptation preceding
adaptation to 11,200 millilamberts.

In a later series of experimental sessions threshold determinations
were made after one second of dark adaptation using the timing mechanism
described above. One second before the end of light adaptation the
experimenter said "ready", and then threw the switch which caused shutter D
to close and the timer to start. Immediately after throwing the switch the
experimenter shifted the lever, thereby changing to the optical system used
for presentation of test flashes and reopening shutter D. At one second
after shutter D closed terminating light adaptation, the timer circuit
closed, tripping shutter S and presenting the first test flash. In order
to provide a check on possible variation in threshold between the earlier
experimental sessions and those in which the thresholds after one second
of dark adaptation were determined, thresholds at one, three, and five
minutes were redetermined in the latter sessions. Good agreement with the
earlier determinations was obtained.

The gratings were randomly positioned so that the lines appeared
to the observer as vertical, inclined 45 degrees clockwise from vertical,
or inclined 45 degrees counterclockwise from vertical. The observer
responded after any test flash either by identifying the position of the
grating, or by saying "no" if he did not see the grating. The small num-
ber of wrong responses were counted the same as negative responses.

During the first experimental session in the determination of the
threshold curve for a given grating at a given level of preadaptation,
the experimenter attempted to adjust successive flash luminances so that
there was frequent alternation between correct identifications of grating
position and negative responses. It was then attempted in subsequent
sessions to obtain both correct and negative responses at each of the
seventeen times during dark adaptation when flashes were presented. When
the highest luminance at which a negative response was obtained and the
lowest luminance at which the position of the grating was correctly iden-
tified did not differ by more than 0.3 log unit, the midpoint between
these two values was taken as the threshold point. A sufficient number
of points to determine the threshold curve was usually obtained in four
or five sessions.

The specific method used in this experiment for the determination of threshold was necessitated by the fact that threshold luminance for resolution of the gratings was considerably higher than the light detection threshold, approximately three log units higher in the case of the finest grating. The method of limits was not used, therefore, as frequent test flashes might have altered the course of dark adaptation. A check experiment performed in the preceding study by Brown, Graham, Leibowitz, and Ranken, indicated that flashes at two minute intervals did not have any appreciable effect on subsequent determinations, even at luminances more than a log unit higher than any of those used at a comparable degree of dark adaptation in the present study. Subsequent checks of the effect of different flash intervals indicate that flashes spaced less than one minute apart have no effect on subsequent determinations at the highest luminances used in the present experiment.

RESULTS

Tables I, II, III and IV contain the threshold values of log luminance for each grating used with each of the four preadapting luminances: 11,200, 1290, 100, and 0.98 millilamberts. The results are presented graphically in Figures 2, 3, 4, 5 and 6. Figure 2 affords a comparison of the course of threshold for light detection during dark adaptation with each of the three preadaptation luminances.

Figure 2 shows that as luminance of the preadaptation light increases, dark adaptation takes place more slowly, i.e., threshold decrease is at a more gradual rate. With the two highest preadapting luminances there is a rod-cone break for both observers. No discernible break occurs with the two lower preadapting luminances; this may be interpreted to mean that rod adaptation is so rapid that it completely obscures any cone adaptation.

There are three points where the plotted curves for ER cross. The final cone threshold after light adaptation at 11,200 millilamberts falls below the final cone threshold after adaptation at 1290 millilamberts, a similar result is found in the final rod thresholds for these two conditions, and final rod threshold after adaptation at 100 millilamberts falls below final rod threshold after adaptation at 0.98 millilamberts. It is probable that these results are indicative of a change in ER's threshold or threshold criterion, in the time elapsed between determinations of the different functions. Such a conclusion is strengthened by the fact that similar results are not found in the data of JB. Comparable curves were obtained in the same sequence and over the same time period for both observers. Therefore, if the effects cited in the data of ER resulted from some change in the apparatus, similar effects should appear in the data of JB.

In spite of these anomalies, the important effects of increased adapting luminance are not obscured. The highest initial threshold values are found with the highest adapting luminance, and as adapting luminance is decreased threshold luminance approaches a minimum value earlier in the course of dark adaptation.

TABLE I

Log threshold luminance in millilamberts at different times in the dark for different visual acuities and for no grating. Luminance of preadapting light: 11,200 millilamberts. Duration of preadaptation: 5 minutes. 3 mm artificial pupil. Duration of flash: 0.04 seconds. Field diameter: 7.3 degrees. Observers ER and JB.

LOG THRESHOLD LUMINANCE

TIME (min)	Visual acuity = 0.62		0.25		0.042		No grating	
	ER	JB	ER	JB	ER	JB	ER	JB
0.017	2.42	2.57	1.80	1.82	1.40	1.42	1.10	1.15
0.083	1.82	2.42	1.24	1.62	0.76	1.22	0.15	0.70
1	1.40	1.04	0.44	0.18	0.15	-0.21	-0.25	-1.05
3	0.14	-0.26	-0.95	-1.02	-1.45	-1.25	-2.05	-1.50
5	-0.45	-0.50	-1.20	-1.25	-1.60	-1.55	-2.05	-1.60
7	-0.55	-0.50	-1.50	-1.30	-1.80	-1.65	-2.20	-1.75
9	-0.60	-0.55	-1.50	-1.35	-1.95	-1.70	-2.11	-1.80
11	-0.65		-1.45	-1.35	-1.95	-1.65	-2.11	-1.95
13		-0.60	-1.45	-1.40	-1.95	-1.75	-2.26	
15	-0.60	-0.60	-1.60	-1.50	-2.05	-1.95	-2.31	-2.41
17	-0.55	-0.65	-1.55		-2.20	-2.30	-2.66	-2.61
19	-0.60	-0.60		-1.50	-2.33	-2.35	-2.86	-2.91
21	-0.60	-0.65	-1.60		-2.41	-2.23	-3.11	-3.01
23	-0.65		-1.45	-1.45	-2.41	-2.33	-3.37	-2.96
25	-0.65	-0.50	-1.65	-1.40	-2.41	-2.51		-3.06
27	-0.55	-0.70	-1.60	-1.50	-2.36	-2.56	-3.37	-3.16
29	-0.60	-0.60		-1.45	-2.46	-2.71	-3.47	-3.21
31	-0.65	-0.65	-1.60		-2.51	-2.85	-3.68	-3.26

TABLE II

Log threshold luminance in millilamberts at different times in the dark for different visual acuities and for no grating. Luminance of preadapting light: 1290 millilamberts. Duration of preadaptation: 5 minutes. 3 mm artificial pupil. Duration of flash: 0.04 seconds. Field diameter: 7.3 degrees. Observers ER and JB.

LOG THRESHOLD LUMINANCE

TIME (min)	Visual acuity = 0.62		0.25		0.042		No grating	
	ER	JB	ER	JB	ER	JB	ER	JB
0.017	1.35	1.10	0.74	0.49	0.14	0.19	-0.16	0.14
0.083	1.25	1.05	0.69	0.24	-0.06	-0.16	-0.41	-0.36
1	0.44	0.04	-0.45	-0.55	-1.05	-0.80	-1.20	-0.90
3	0.09	-0.36	-1.00	-1.15	-1.66	-1.46	-1.71	-1.71
5	-0.66	-0.46	-1.30	-1.30	-1.76	-1.51	-1.76	-1.76
7	-0.46	-0.36	-1.30	-1.25	-1.76	-1.61	-1.76	-1.81
9	-0.56	-0.36	-1.30	-1.35	-1.71	-1.71	-1.96	-1.76
11	-0.61	-0.51		-1.35	-1.86	-1.71	-2.31	-2.36
13		-0.51	-1.30	-1.35	-2.26	-2.11	-2.81	-2.41
15	-0.51	-0.56	-1.25	-1.35	-2.31	-2.26	-2.81	-2.61
17	-0.61	-0.56	-1.30		-2.36	-2.36	-3.18	-3.03
19	-0.46	-0.51	-1.25	-1.35	-2.71	-2.46	-3.13	-3.33
21	-0.41	-0.61			-2.71	-2.41	-3.38	-3.48
23	-0.46	-0.61	-1.30	-1.35		-2.46	-3.28	-3.33
25	-0.41	-0.61	-1.30		-2.71		-3.23	-3.38
27		-0.66	-1.25	-1.35		-2.71	-3.18	
29	-0.46	-0.61		-1.35	-2.66			-3.48
31	-0.46	-0.66	-1.25	-1.40	-2.66	-2.96	-3.38	-3.58

TABLE III

Log threshold luminance in millilamberts at different times in the dark for different visual acuities and for no grating. Luminance of preadapting light: 100 millilamberts. Duration of preadaptation: 5 minutes. 3 mm artifical pupil. Duration of flash: 0.04 seconds. Field diameter: 7.3 degrees. Observers ER and JB.
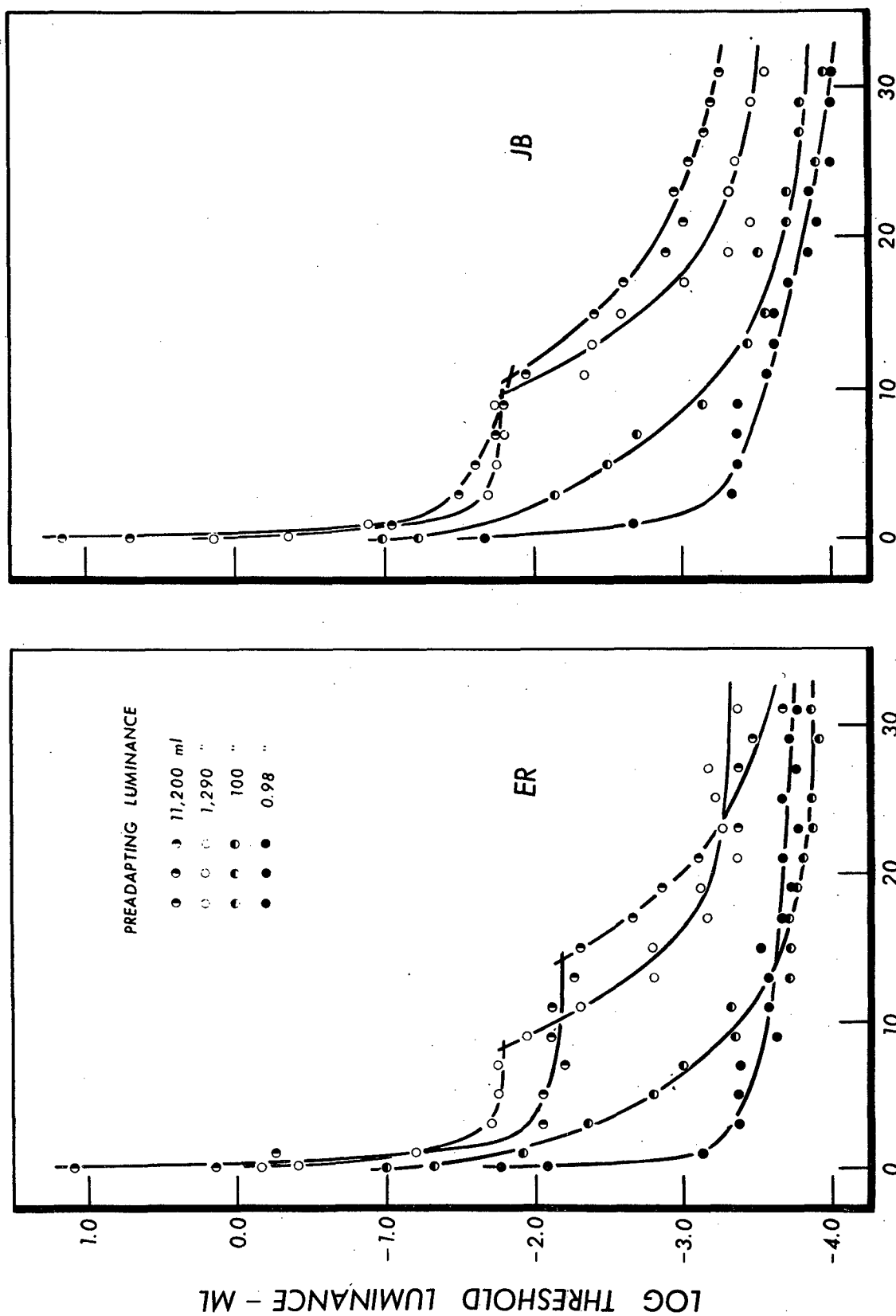
LOG THRESHOLD LUMINANCE

TIME (min)	Visual acuity = 0.62		0.25		0.042		No grating	
	ER	JB	ER	JB	ER	JB	ER	JB
0.017	0.79	0.19	-0.46	-0.40	-1.00	-0.90	-1.00	-1.00
0.083	0.54	0.14	-0.70	-0.60	-1.31	-1.10	-1.33	-1.25
1	-0.11	-0.51	-1.25	-0.75	-1.75	-1.75	-1.93	
3	-0.41	-0.41	-1.30	-1.15	-2.05	-1.95	-2.36	-2.16
5	-0.45	-0.46	-1.30	-1.15	-2.18	-2.20	-2.81	-2.51
7	-0.36	-0.51	-1.40	-1.15	-2.31	-2.31	-3.01	-2.71
9	-0.41	-0.66	-1.30	-1.25	-2.61	-2.51	-3.36	-3.16
11	-0.41	-0.56	-1.35	-1.30	-2.86	-2.56	-3.33	
13	-0.41	-0.56	-1.35		-2.91	-2.61	-3.73	-3.46
15	-0.46	-0.61	-1.35	-1.25	-2.91	-2.81	-3.73	-3.58
17	-0.41	-0.61		-1.20	-2.86	-2.96	-3.73	
19	-0.51	-0.61		-1.25	-2.86	-2.96	-3.78	-3.53
21	-0.26	-0.56	-1.35		-3.01	-3.01	-3.83	-3.73
23	-0.36	-0.61		-1.40	-3.06	-3.11	-3.88	-3.73
25	-0.36	-0.71	-1.40	-1.25	-3.01	-3.16	-3.88	-3.93
27	-0.36	-0.56	-1.30	-1.25		-3.21		-3.83
29	-0.46	-0.71	-1.40	-1.25	-2.96	-3.21	-3.93	-3.83
31	-0.41	-0.51	-1.35	-1.30	-3.06		-3.88	-3.98

TABLE IV

Log threshold luminance in millilamberts at different times in the dark for different visual acuities and for no grating. Luminance of preadapting light: 0.98 millilambert. Duration of preadaptation: 5 minutes. 3 mm artificial pupil. Duration of flash: 0.04 seconds. Field diameter: 7.3 degrees. Observers ER and JB.

LOG THRESHOLD LUMINANCE

TIME (min)	Visual acuity = 0.62		0.25		0.042		No grating	
	ER	JB	ER	JB	ER	JB	ER	JB
0.017	-0.11	-0.19	-0.82	-1.02	-1.59	-1.47	-1.79	-1.69
0.083	-0.17	-0.37	-1.14	-1.02	-1.69	-1.49	-2.09	-1.69
1	-0.27	-0.44	-1.54	-1.09	-2.44	-2.29	-3.14	-2.69
3	-0.39	-0.50	-1.54	-1.44	-2.73	-2.69	-3.39	-3.33
5	-0.39	-0.64	-1.49	-1.39	-2.83	-2.94	-3.38	-3.38
7	-0.27	-0.64		-1.49	-2.93	-3.04	-3.38	-3.38
9		-0.50	-1.44	-1.44		-3.09	-3.63	-3.38
11	-0.39	-0.60	-1.54	-1.39	-3.03	-2.99	-3.58	-3.58
13	-0.37		-1.59	-1.34	-2.93	-3.14	-3.58	-3.63
15	-0.39		-1.54	-1.34	-2.98		-3.53	-3.63
17	-0.27	-0.55	-1.44	-1.34	-2.93	-3.24	-3.68	-3.73
19		-0.65			-2.98	-3.14	-3.73	-3.88
21	-0.29	-0.70	-1.53	-1.29	-2.98	-3.29	-3.68	-3.93
23		-0.50					-3.78	-3.88
25	-0.39	-0.60	-1.44	-1.44			-3.68	-4.03
27		-0.55				-3.41	-3.78	
29	-0.47		-1.64	-1.34	-3.07		-3.73	-4.03
31		-0.55					-3.78	-4.03

Figure 2. Luminance thresholds for light detection during dark adaptation after preadaptation to luminances of 11,200, 1290, 100, and 0.98 millilamberts. Data for observers ER and JB.

Differences in the lowest rod thresholds reached with different conditions of light adaptation for JB may indicate that for higher light adaptation luminances 30 minutes of dark adaptation does not provide sufficient time to reach a limiting threshold value. It was recently reported by Wald and St. George (17) that after light adaptation to a luminance of 10,000 millilamberts, dark adaptation was not complete after more than four hours in the dark.

The family of curves obtained with a preadapting luminance of 11,200 millilamberts is presented in Figure 3. It will be noted that the curves for light detection and for the coarsest grating representing a visual acuity of 0.042 both show a rod-cone break, while the curves for the two finer gratings representing visual acuities of 0.25 and 0.62 do not show a rod portion. This observation is in accord with the results of Brown, Graham, Leibowitz, and Ranken for a preadapting luminance of 1500 millilamberts. The two upper curves of Figure 3 for the two finest gratings appear to be parallel with respect to the ordinate, with the upper curve approximately 0.8 log unit higher for both observers. The cone portions of the curves for light detection and for a visual acuity of 0.042 are approximately parallel to the two upper curves, while the rod portions show a subsequent further decline in the threshold value after the cone threshold appears to have reached a minimal value. The rod portions for light detection and for the coarsest grating do not appear to be of the same form for either of the subjects and also differ between the two observers. The minimal threshold value for light detection for ER is below that for JB, while the minimum threshold for the coarsest grating is lower for JB than for ER. The break occurs at about the same point in time in both of the curves for ER, while for JB the break seems to occur later in the acuity function than in the light detection function. Considering the scatter of the points and the arbitrary method of fitting the curves, special significance cannot be attached to differences in the positions of the breaks.

Figure 4 presents curves obtained after preadaptation to 1290 millilamberts. In general they are quite similar to the curves of Figure 3. The curves for light detection and the lowest visual acuity both show a rod-cone break, while the curves for visual acuities of 0.25 and 0.62 do not. Initial thresholds are somewhat lower for all the curves in Figure 4 than for comparable curves in Figure 3, and in general limiting threshold values are approached more rapidly. Separation of the curves with respect to the ordinate is of the same order as that found in Figure 3. Cone portions of the curves representing the data of ER appear to be parallel with respect to the ordinate, but there are some deviations from parallel in the comparable data of JB. The curve representing threshold for a visual acuity of 0.62 continues to descend very gradually out to 30 minutes of dark adaptation, while the curve for a visual acuity of 0.25 appears to have reached a limiting value after 10 minutes of dark adaptation. However, in view of the small amount of change in threshold between 10 and 30 minutes of dark adaptation for the 0.62 visual acuity curve, and the fact that a similar decline is not found in any of the other curves at this value of visual acuity for either observer, the deviation is of doubtful significance. As in Figure 3, rod portions of the curves in Figure 4 differ in form.

Curves obtained with 100 millilamberts preadaptation are presented in Figure 5. All of the curves appear to start at a lower initial level than comparable curves in Figures 3 and 4 and represent a more rapid decline in the threshold value. In the data of Figure 5, as in Figures 3 and 4, the two curves representing the two highest acuities are approximately parallel with respect to the ordinate, and differ from both the light detection curve and the curve for the lowest visual acuity. The two curves for lowest acuity and for light detection appear in this case to represent predominantly rod function. There is no observable break in these curves. The points of the curves are close together in the early part of dark adaptation, and the curves seem to differ in form.

Figure 6 presents the curves obtained with a preadapting luminance of 0.98 millilambert. These curves have lower initial values and appear to reach final threshold more quickly than any of the preceding sets of curves. The curve representing luminance threshold for the highest acuity value appears to decline somewhat less than the curve representing an acuity of 0.25 for ER, while the same curves for JB appear nearly parallel. The curves for an acuity of 0.042 and for light detection are nearly parallel for both observers and show a much greater initial decline in threshold than do either of the two upper curves. Presumably the course of the two lower curves is determined by rod function.

After 31 minutes of dark adaptation, threshold luminances for visual acuities of 0.62 and 0.25 are very nearly the same for all preadapting luminances. The few slight differences in final threshold bear no systematic relation to differences in light adaptation. For a visual acuity of 0.042, however, the threshold after 31 minutes of dark adaptation is systematically higher for higher preadapting luminances. These thresholds are believed to be determined by rod function. The increase in these thresholds may indicate that more than 30 minutes are required for complete dark adaptation of the rods after all but very low light adapting luminances. Final light detection thresholds for JB also appear to increase with increased light adapting luminance. Differences in the final light detection thresholds of ER may reflect the lack of a stable criterion for this function.

DISCUSSION

The data of Figures 3, 4, 5 and 6 show that form of luminance threshold curves during dark adaptation is little influenced by the criterion of threshold. Initial threshold luminances are high, and as dark adaptation continues, threshold decreases with decreasing negative slope, although the exact form of the curves and the range of luminances covered depend on the conditions of preadaptation. When there is a rod-cone break in the threshold curve for light detection, such a break is also found in the threshold curves for the resolution of relatively gross detail.

Variation in visual acuity has two effects on the curves. First, it may be considered as a parameter which determines the position of the curves on the log luminance axis. As visual acuity is increased, the threshold
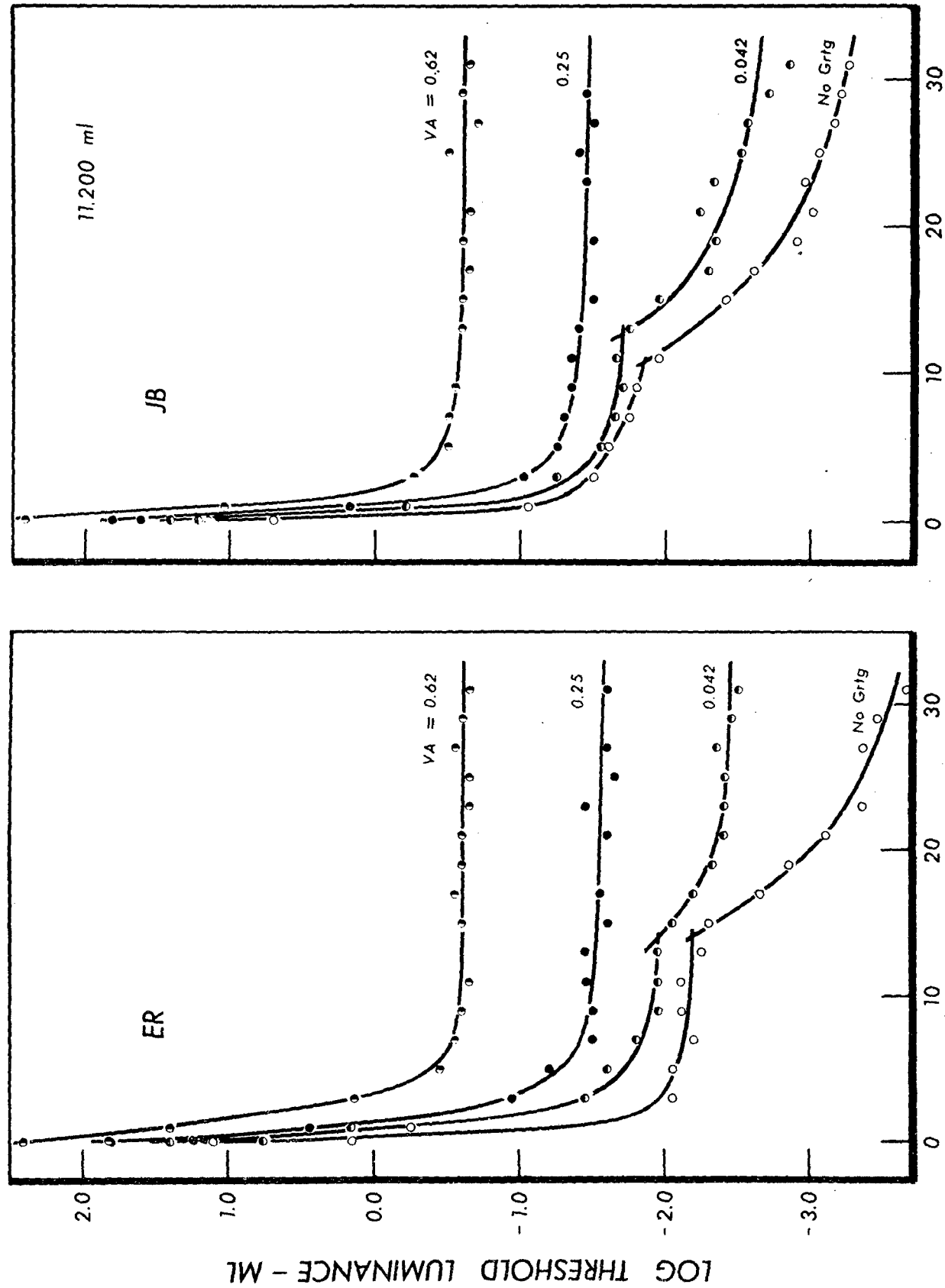
Figure 3. Luminance thresholds for different acuities and for light detection (no grating) during dark adaptation after five minutes preadaptation of 11,200 millilamberts. The number beside each curve refers to the level of acuity. Data for observers ER and JB
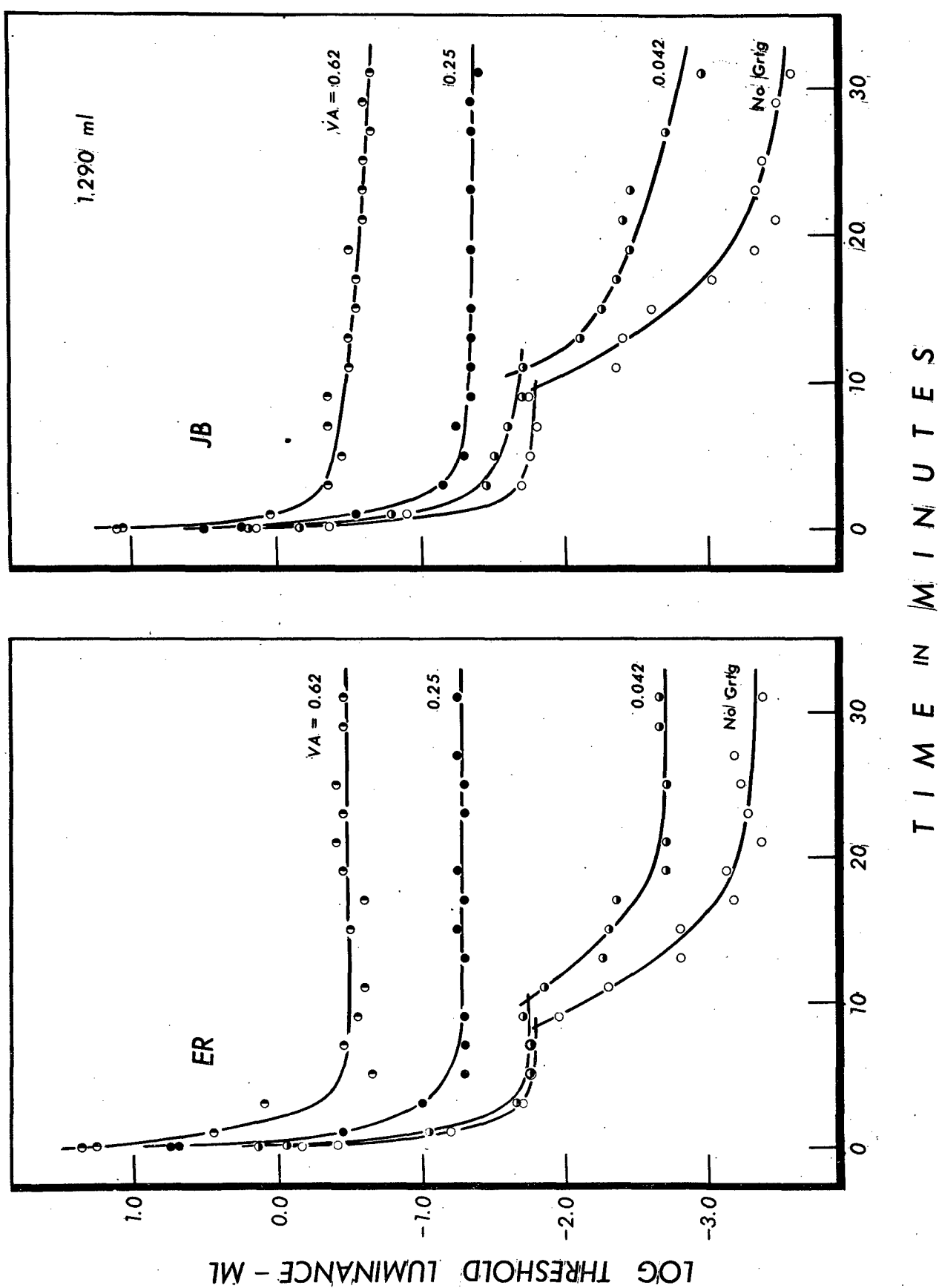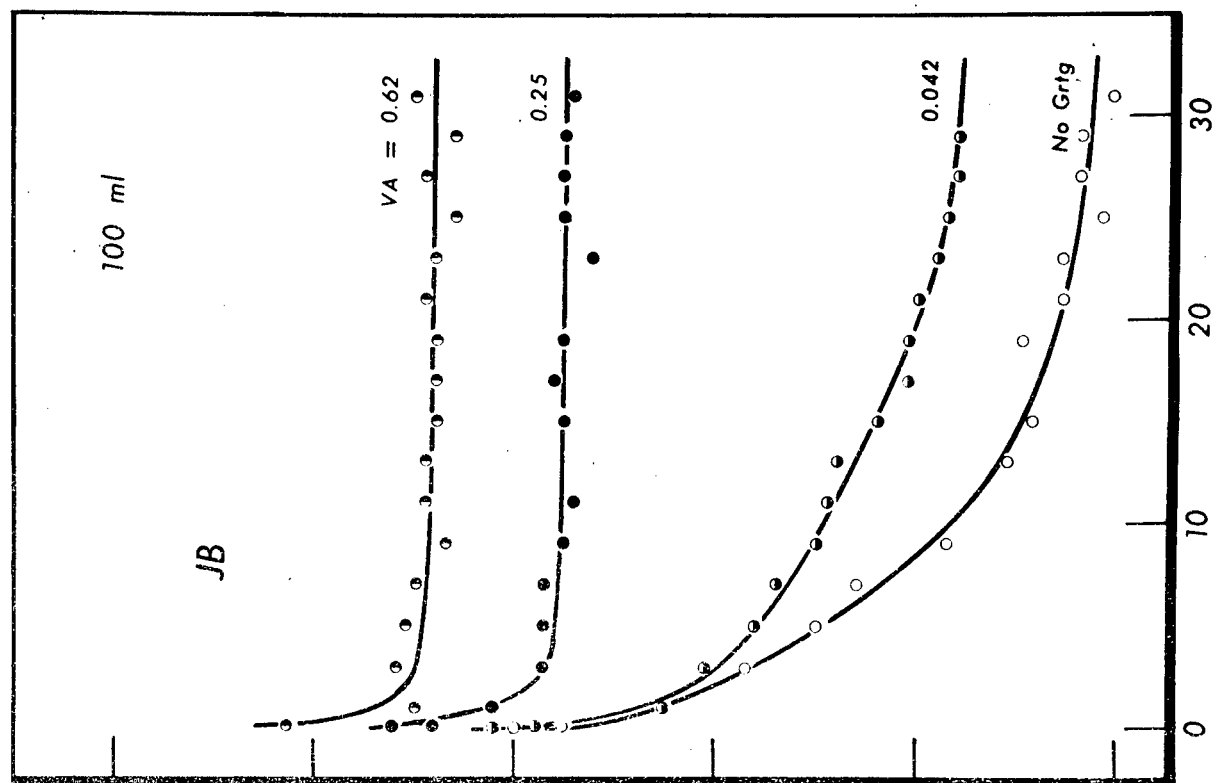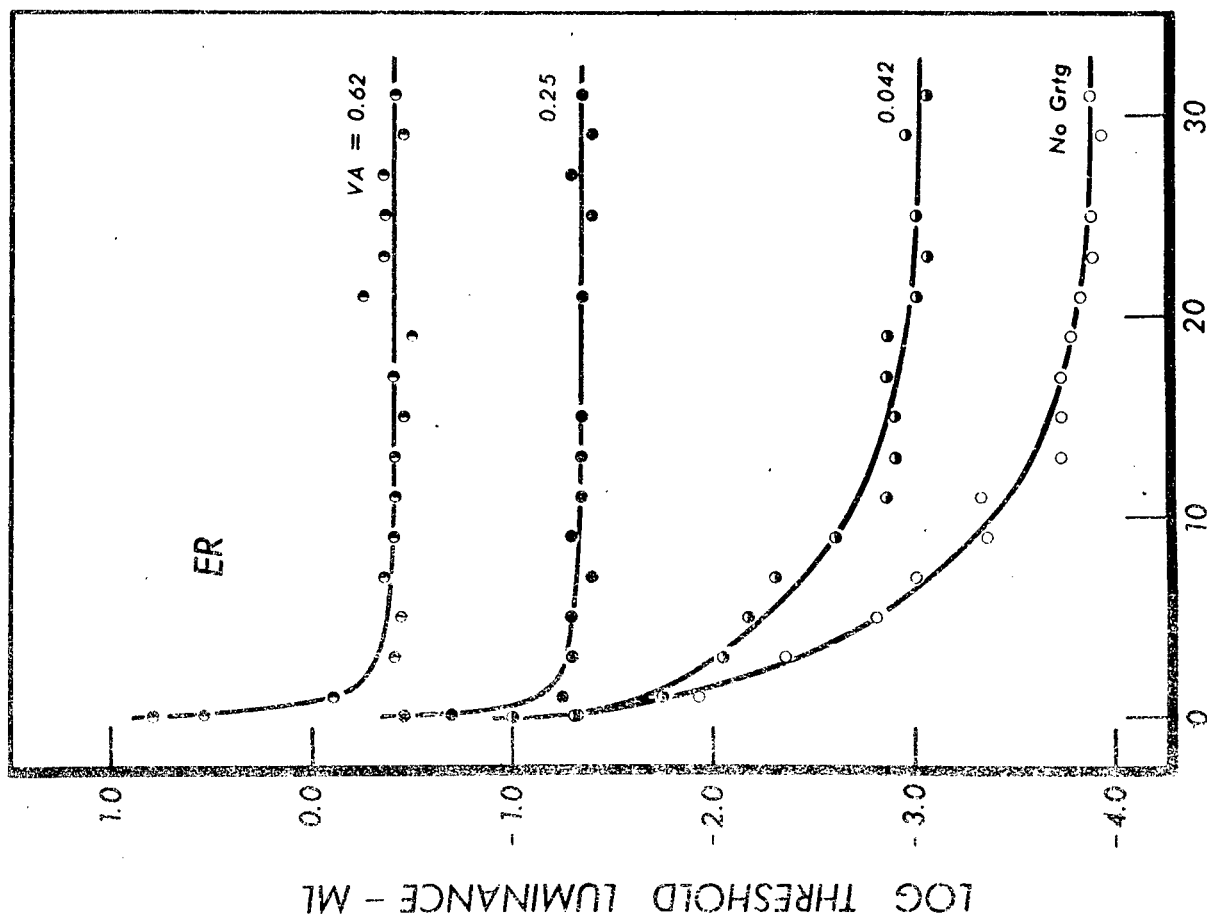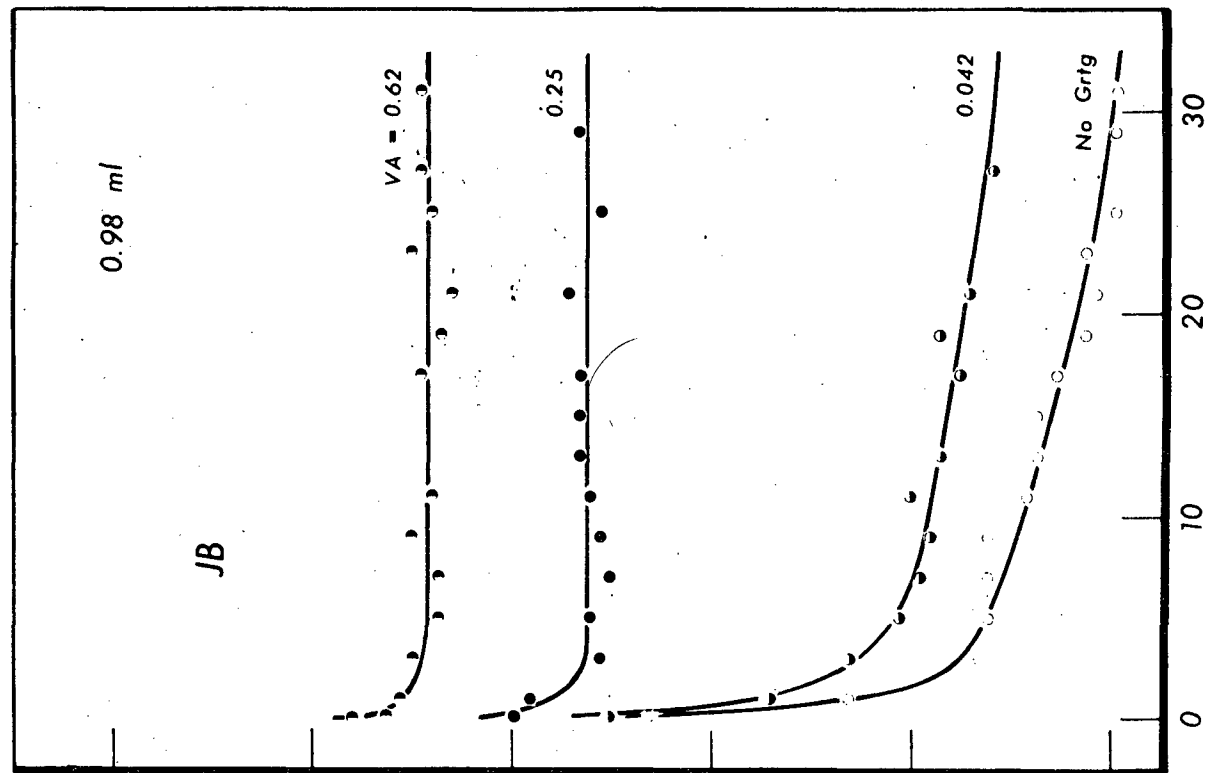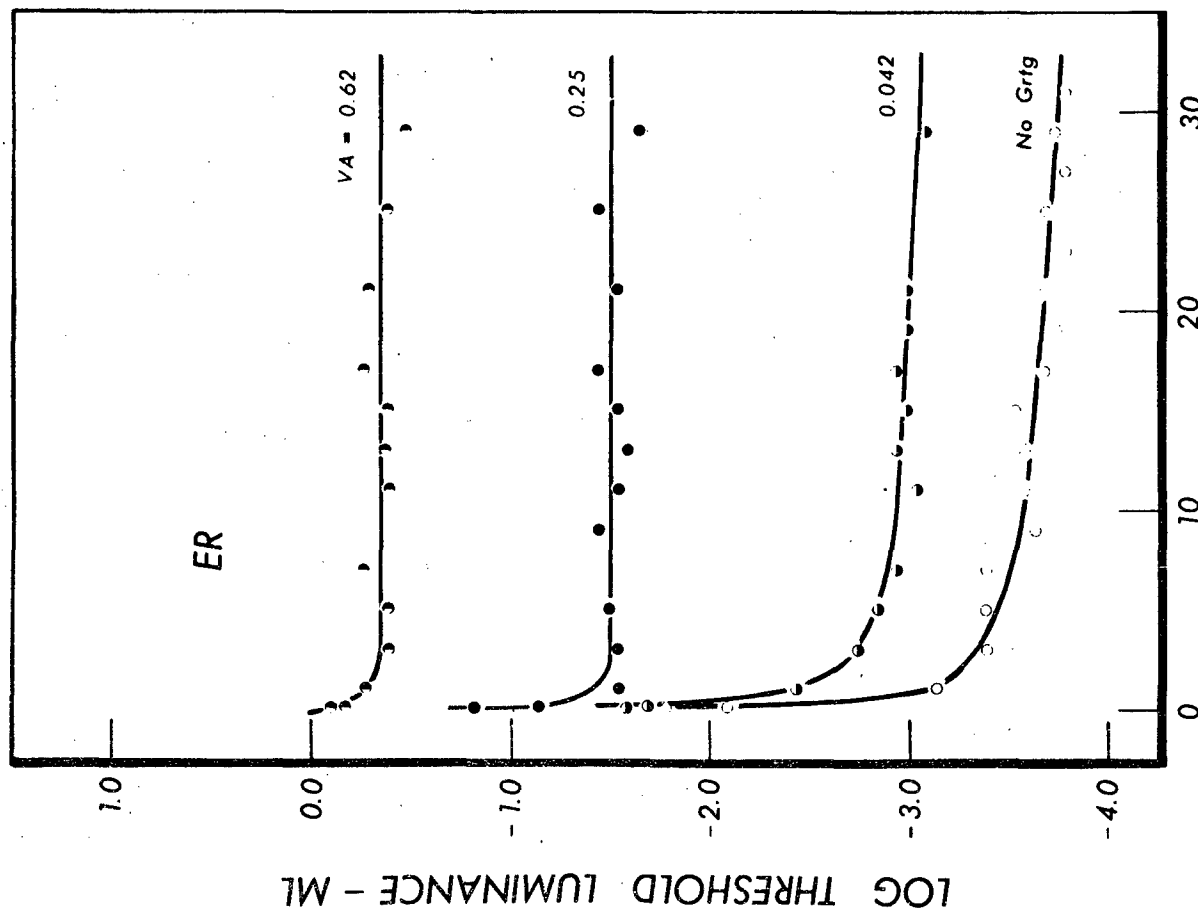
Figure 4. Luminance thresholds for different acuities and for light detection (no grating) during dark adaptation after five minutes preadaptation of 1290 millilamberts. The number beside each curve refers to the level of acuity. Data for observers ER and JB.

Figure 5. Luminance thresholds for different acuities and for light detection (no grating) during dark adaptation after five minutes preadaptation of 100 millilamberts. The number beside each curve refers to the level of acuity. Data for observers ER and JB.

Figure 6. Luminance thresholds for different acuities and for light detection (no grating) during dark adaptation after five minutes preadaptation of 0.98 millilambert. The number beside each curve refers to the level of acuity. Data for observers ER and JB.

curves are displaced upward on this axis. Second, the level of visual acuity determines whether or not there will be any portion of the curves similar in form to those portions of curves for light detection which are descriptive of rod function. For visual acuities of 0.25 and above no rod portions are found.

The effect of raising the level of the preadapting luminance is the same on all the curves. With an increase in the preadapting luminance, the initial threshold values are raised, and the decrease in threshold during dark adaptation occurs at a more gradual rate. After thirty minutes of dark adaptation, however, there is very little difference in the threshold luminance for any given acuity regardless of the preadapting luminance. Definite rod-cone breaks are not found when the level of preadaptation is 100 millilamberts or below, but there is a well defined break with a preadapting luminance of 1290 millilamberts and above. When the level of visual acuity is sufficiently high that the rods, which require longer to reach maximum sensitivity, do not make any significant contribution to resolution, minimum luminance threshold may be reached within five or ten minutes, even with preadaptation of higher than 10,000 millilamberts.

It is of considerable practical interest to consider the effect of the level of preadaptation on the threshold luminance for resolution of visual detail in the initial stage of dark adaptation. The curves presented in Figure 7 indicate the character of this relation for three levels of visual acuity and for light detection. Each of the plotted points represents an average value for the two observers after one second of dark adaptation. The deviation in form of the light detection curve is characteristic of both observers.

Here as in the previous figures, the curves are nearly parallel with respect to the log luminance axis for visual acuities of 0.62, 0.25, and 0.042. As the log preadapting luminance is increased, log threshold luminance also increases at an accelerating rate. It would appear that at a level of preadaptation somewhat higher than 10,000 millilamberts, threshold luminance may approach an infinite value. Beyond this value of preadaptation it would presumably be impossible to resolve visual detail after one second of dark adaptation no matter how high a luminance is used.

Figure 8 illustrates the relation between log visual acuity and log preadapting luminance. The solid curves were calculated from Figure 7 by the intersections of lines drawn parallel to the axis of log preadapt-luminance at log threshold luminance values of 1.0, 0.0, and -0.8 millilamberts. They therefore represent the relation after one second of dark adaptation. The dashed curves were calculated in a similar manner from data after five seconds of dark adaptation. As preadapting luminance is increased, there is an initial gradual decline in log visual acuity followed by a rapid decline until at some limiting level of preadaptation it is no longer possible to resolve even the most gross visual detail in the early stages of dark adaptation. The higher the luminance of the test flash, the higher is the initial level of visual acuity, and the higher is
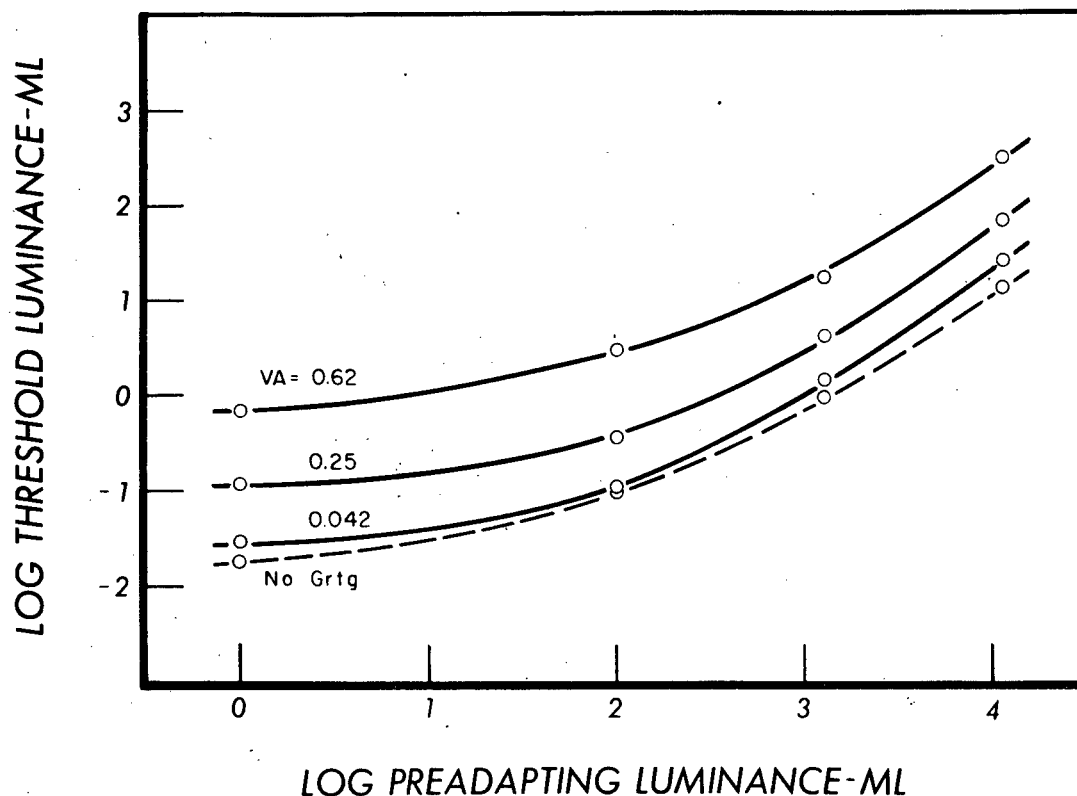
Figure 7. Luminance thresholds for different acuities and for light detection (no grating) after one second dark adaptation as a function of preadapting luminance. The number beside each curve refers to the level of acuity. Points represent average values for both observers.
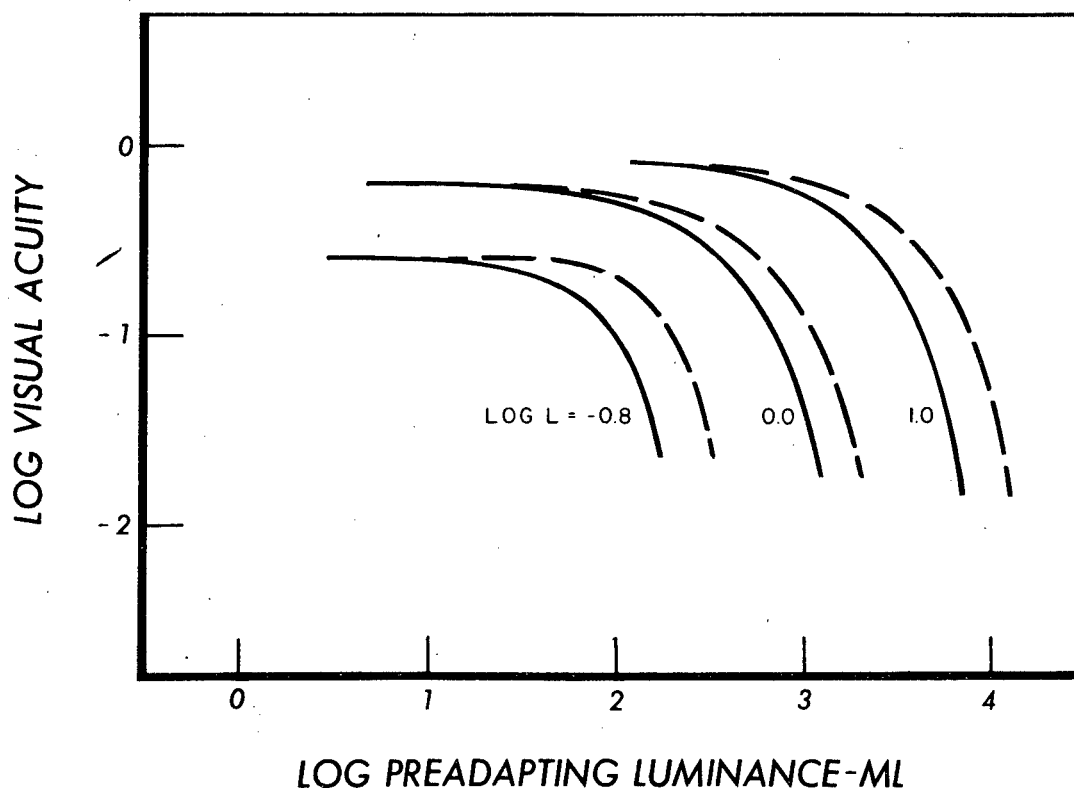

Figure 8. Visual acuity as a function of preadapting luminance. Solid curves are computed from average data after one second dark adaptation. Dashed curves are computed from average data after five seconds dark adaptation. The number beside each curve specifies log grating luminance.

the limiting preadaptation luminance. A slight increase in dark adaptation duration does not raise the initial level of visual acuity, but does increase the limiting light adaptation luminance for a given test flash luminance. Inspection of the solid curves of Figure 8 indicates that for all three test flash luminances there is a difference of approximately 1.7 log units between log test flash luminance and the log preadapting luminance at which rapid decline in log visual acuity begins. Therefore, it may be concluded that as long as the ratio of light adaptation luminance to test flash luminance is less than 500 to one, visual acuity after one second of dark adaptation will not be appreciably diminished. From the dashed curves of Figure 8 it may similarly be concluded that visual acuity after five seconds of dark adaptation will not be appreciably diminished if the ratio of adapting luminance to test flash luminance is less than 1000 to one. From these data it is possible to specify the brightness differentials that can be tolerated in the performance of many common Air Force tasks.

In attempting to present a theoretical formulation of the changes which occur in the threshold luminance for resolution of an acuity object during dark adaptation, we might assume the following relation as descriptive of the dependence of visual acuity on energy of stimulation and the sensitivity of the retinal receptors involved in the mediation of visual acuity:

$$VA = F[It \times f_1(S,P,A,.....)]$$ (1)

where $f_1(S,P,A,.....)$ represents receptor sensitivity in terms of the chemical materials involved, I represents the luminance of the test field, and t is the duration of the test flash. Test flash energy and the sensitivity of the receptors are therefore assumed to be reciprocally related for the resolution of a given acuity test object. No assumptions are made regarding the nature of the relation of acuity threshold to either of these two variables. From (1), the threshold luminance for any degree of visual acuity might be expressed as follows:

$$I = 1/t \times f'(VA) \times f_2(S,P,A,......)$$ (2)

where the exact nature of $f'(VA)$ would depend on the type of acuity object used as well as its minimum visual angle.

Expressed in logarithmic form, (2) becomes:

$$\log I = -\log t + \log f'(VA) + \log f_2(S,P,A,.....)$$ (3)

From (3) it becomes apparent that a graphical presentation of the log threshold luminance as a function of time in the dark for a series of different acuity criteria will consist of a family of curves parallel to the curve for light detection, the position of each of which with respect to the log I axis is determined by the value of log $f'(VA)$. This will be true, of course, only if the nature of the sensitivity function remains the same at different levels of visual acuity. It may further be assumed

that the nature of the sensitivity function will in fact be the same for all values of visual acuity which are mediated by the same kind of receptors. On the basis of this latter assumption and existing evidence of both a physiological and an histological nature, we might predict that the curves may take either one of two distinct forms, one of which is representative of the rods, and the other of which is representative of the cones. We might also predict that the course of threshold luminance during dark adaptation for high levels of visual acuity would depend solely on the cones, while at a certain lower, perhaps critical level of visual acuity the rods would also become functional in the mediation of visual acuity. The exact form of the curves would then depend on the conditions of preadaptation, and the retinal area stimulated by the test flash. At a high level of preadaptation and with stimulation of a portion of the retina containing both rods and cones, curves for high values of visual acuity would be of a form representative of the change in cone threshold. Curves for lower values of visual acuity where the rods could also make some contribution might show an initial portion representative of cones, followed by a subsequent portion representative of rods. With very low levels of preadaptation, the threshold curves for high values of visual acuity might be expected to show no decline at all since there would be little or no subsequent increase in cone sensitivity. The curves for low values of visual acuity would be representative of the rods alone.

A further prediction could be made on the basis of the foregoing assumptions. Since the position of the curves is assumed to be dependent on the specific value of $f'(VA)$ for each curve, then the displacement of any two curves obtained under the same conditions of preadaptation and representative of specific values of visual acuity would be independent of the conditions of preadaptation, i.e., independent of the form of the curves. This would be true only for those portions of the curves representative of the same kind of receptors. For example, if we obtained the threshold curves for VA_1 and VA_2 under condition of preadaptation I, and then determined the threshold curve for VA_1 under condition of preadaptation II, we could construct the threshold curve for VA_2 under condition of preadaptation II. This could be done by simply displacing the curve for VA_1 by the amount the two curves were displaced under condition I.

Receptor sensitivity, expressed by $f_1(S,P,A,.....)$ in the above formulation, was controlled in the present experiment by time in the dark after a given condition of light adaptation. Sensitivity might also be controlled by adapting the eye of the observer to a steady state at various luminance levels. Luminance thresholds for the resolution of a number of acuity objects could then be determined for each adapting luminance. According to the present formulation a plot of the resulting data in terms of log visual acuity as a function of log test flash luminance, with adaptation luminance as a parameter, should result in curves parallel with respect to the abscissa. Curves for increasing adaptation luminance should simply be shifted to the right along the abscissa. Curves for low adaptation luminances would be expected to show rod-cone breaks.

Craik (2) has investigated the relation between visual acuity and test flash luminance for a number of different conditions of light adaptation and presents curves of log visual acuity as a function of log test illumination with adaptation luminance as a parameter. Those portions of his curves which are relevant to the present formulation, i.e., the rising portions, do conform fairly well to predictions based on the present formulation. It should be noted that the test flashes exceeded critical duration and fixation conditions were not controlled.

The data of the present experiment indicate that the above theoretical treatment is in some respects too simple to account for all of the obtained results. Starting with the curves presented in Figure 3 for preadaptation at 11,200 millilamberts, the initial, or cone portions of these curves do appear to be parallel with respect to the log luminance axis. For neither of the two observers, however, do the rod portions of the two lower curves appear to be parallel. It is quite possible that the cones have not reached a final threshold level at the point where the break occurs. The acuity curve beyond this point, that part of the curve which we have designated the rod portion, may actually represent some complex function of both rod and cone dark adaptation. The curves presented in Figure 4 for preadaptation at 1290 millilamberts are quite similar to those in Figure 3. No special significance is attached to the slight difference in shape of the 0.62 acuity curve for JB.

The situation in the case of the data of Figure 5 obtained with preadaptation at 100 millilamberts is quite similar. The two higher curves are nearly parallel and may represent cone adaptation, but the two lower curves differ, with the acuity curve showing a slower rate of decline in threshold luminance. It is possible that the initial portions of those curves where they are close together are more representative of cones than of rods. Dark adaptation experiments using colored light indicate that even when fairly low levels of preadaptation are used and there is no noticeable rod-cone break, color can be perceived in the early part of the curve. This is taken to indicate that the test flash luminance is still within the range of cone sensitivity.

In the results obtained with 0.98 millilambert preadaptation, the curves for light detection and an acuity of 0.042 appear to be parallel with respect to the ordinate. The curve for an acuity of 0.62 shows less change in threshold than the curve for an acuity of 0.25 for ER. Comparable curves for JB appear to be nearly parallel.

Most of the deviations from prediction might be explainable if the transition from rod function to cone function with increasing values of acuity is gradual rather than critical, and individual threshold points in the transition range depend on combined function of rods and cones. If this were the case the deviations cited would be expected, and pure "cone" curves could be obtained only with very high levels of acuity or with small foveal areas. Pure "rod" curves could be obtained only with fairly low visual acuities and either very low levels of preadaptation or stimulation in peripheral areas containing relatively few cones.

In general, the prediction is born out that the separation with respect to the ordinate of the curves for different acuities should be independent of the level of preadaptation. Some of the changes in the relative positions of several of the curves are probably the result of individual variation in final threshold. In those instances where the "rod" thresholds are raised, however, it may be due to the fact that dark adaptation is still incomplete after 30 minutes following high levels of preadaptation.

SUMMARY

1. Luminance thresholds for the resolution of different widths of grating line were determined during dark adaptation after five minutes preadaptation to "white" light (2860°K). Four preadapting luminances were used: 11,200, 1290, 100, and 0.98 millilamberts. Grating lines were illuminated in a centrally fixated test area 7.3 degrees in diameter. The duration of exposure was 0.016 second. Gratings consisted of alternating transparent and opaque lines of equal width. Three different line widths were used, corresponding to visual acuities of 0.62, 0.25, and 0.042.

2. Dark adaptation curves obtained with different degrees of visual resolution as the criterion of threshold have the same characteristic shape as curves for light detection. Curves for the finest gratings, representing high degrees of visual acuity, start at a high initial threshold luminance and drop to a final steady state after about 5 to 12 minutes in the dark. Such curves are characteristic of cone function. Curves for coarser gratings may have a duplex character displaying both cone and rod portions, or after preadaptation to low luminances, may evidence rod function only.

3. Visual acuity is a parameter which determines the position of the curve for a given acuity on the log threshold luminance axis. The higher the degree of visual acuity, the higher the position of the curve.

4. Level of preadaptation affects the shape of the curves. The higher the level of preadaptation, the higher the initial threshold luminance and the more gradual the decline to a final steady level. Rod-cone breaks do not occur at the lowest preadapting luminances: 100 and 0.98 millilamberts.

5. After one second of dark adaptation, the relation between the log threshold luminance for resolution of any given visual detail and the luminance of preadaptation is a curve that rises with an increasing slope. After more extended dark adaptation, the level of the preadapting luminance has little effect on threshold for a given acuity.

6. Log visual acuity after very short periods of dark adaptation decreases for all test flash luminances with an increase in log preadapting luminance. The higher the test flash luminance, the higher is the maximum level of visual acuity, and the later does the curve approach an infinite negative slope.

7. A possible theoretical basis for the results is discussed.

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